National Aeronautics and Space Administration

Northern Ohio Energy Storage and Integration Workshop

A Partnership between the Northern Ohio Energy Storage Community, DOE and National Laboratories

A REVIEW OF ENERGY STORAGE TECHNOLOGIES FOR AUTOMOTIVE APPLICATIONS

Kenneth P. Dudek, PhD

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- CEO and Founder of CAR Technologies LLC
- Adjunct CAR Fellow at the Ohio State University/Center for Automotive Research
- 25-year General Motors R&D & Powertrain
- Boss Kettering Award Winner
- Over 30 patents in controls arena
- B.S, M.S., PhD Electrical Engineering
  Notre Dame University

CAR TECHNOLOGIES ®

Robert P. Lane, MBA

- EVP and Founder of CAR Technologies LLC
- 16-year Automotive Industry Consulting and Engineering Services – Alternative Fuel Vehicles
- 2009 Responsible for $278M of the $1.4B of ARRA Grant Activity (20%)
  - Cell and Pack Manufacturing
  - Commercial Vehicle Electrification
  - Fuel Efficient Components (hybrid transmissions)
- Launched CAR Technologies in 2009
- B.S. University of Tennessee, MBA
  Emory University

CAR TECHNOLOGIES ®

- **CAR Technologies LLC**
  - **Facilities construction started in 2010**
  - **Tier 1 to Vehicle and Battery OEMs**
  - **Characterization, Performance, and Durability Testing**
  - **Cell, Module and Pack FMEA**
  - **Battery Management Systems (HW, SW, Algorithms)**
- **Columbus, OH Lab**
  - **120 channel of 0-8V, 400 amp cell cycling**
    - **10 mA, 10 mV measurement accuracy**
  - **10 channels of pack cycling**
  - **Wet labs; High temperature water baths**
  - **Electron Microscopy; X-ray Diffraction on site**
- **Coming to Warren, OH**
  - **TBEIC partner**

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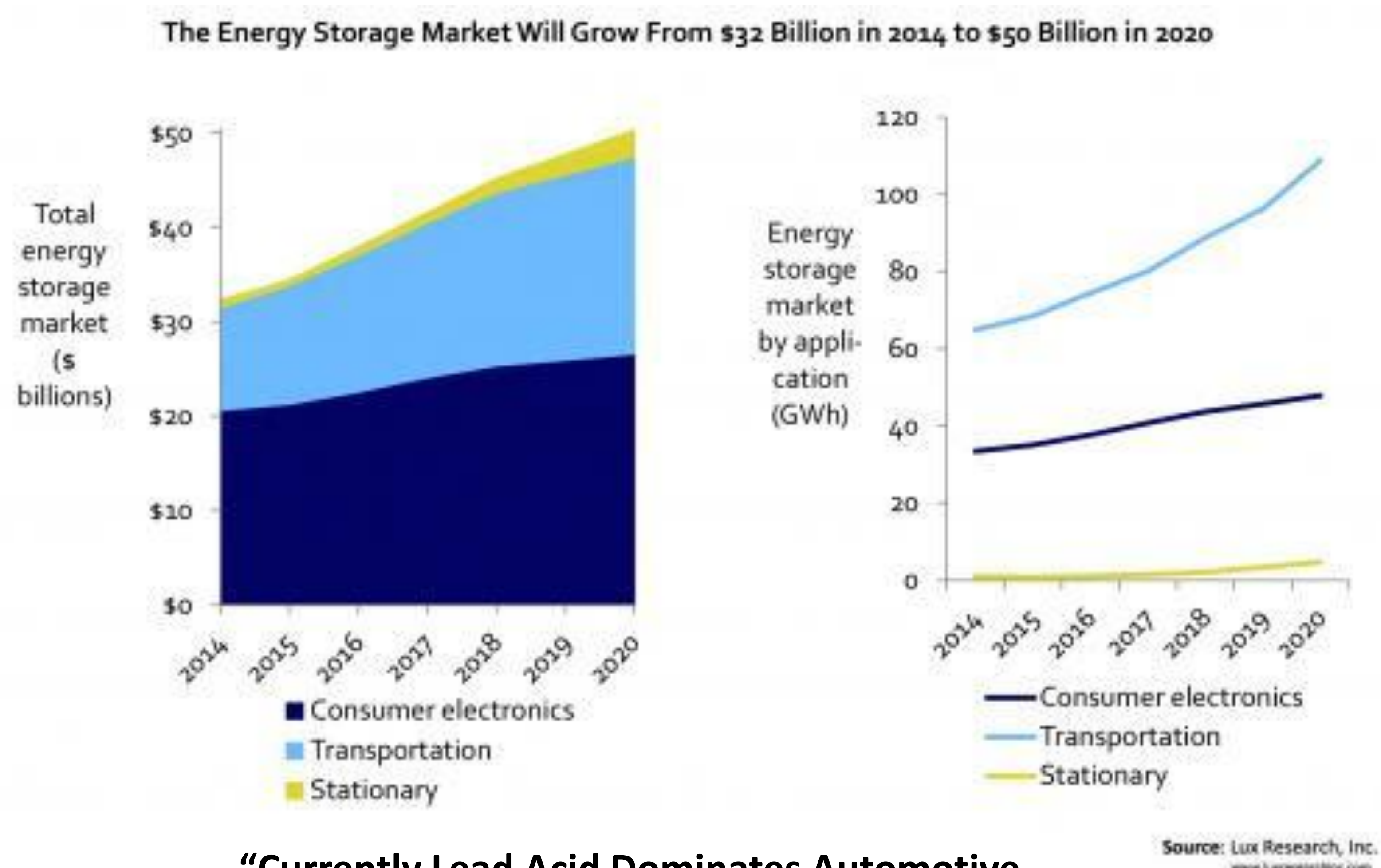
The Need for Energy Storage in the Automotive Industry



"Currently Lead Acid Dominates Automotive Energy Storage" (Lithium Ion Coming On Strong)

Adoption of Energy Storage in the Automotive Industry

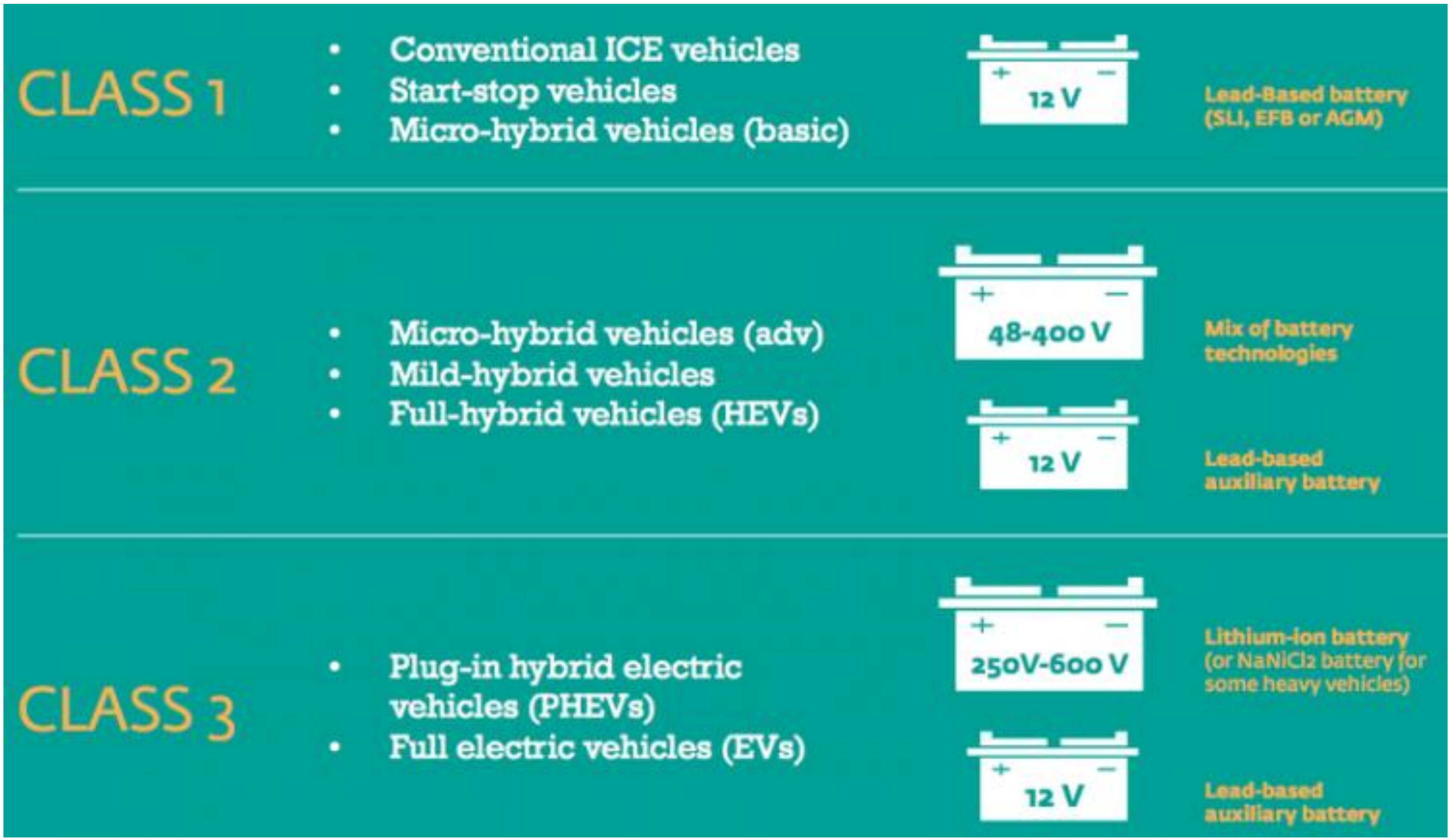
Drivers

- Regulatory/Policy
  - CAFE Standards
  - CARB
  - Carbon Markets?
- Experience with Energy Storage Manufacturers
- Incentives
  - For now
- Risk vs. **Reward**
  - Emission free (kind of)
  - Electric propulsion can have awesome vehicle performance

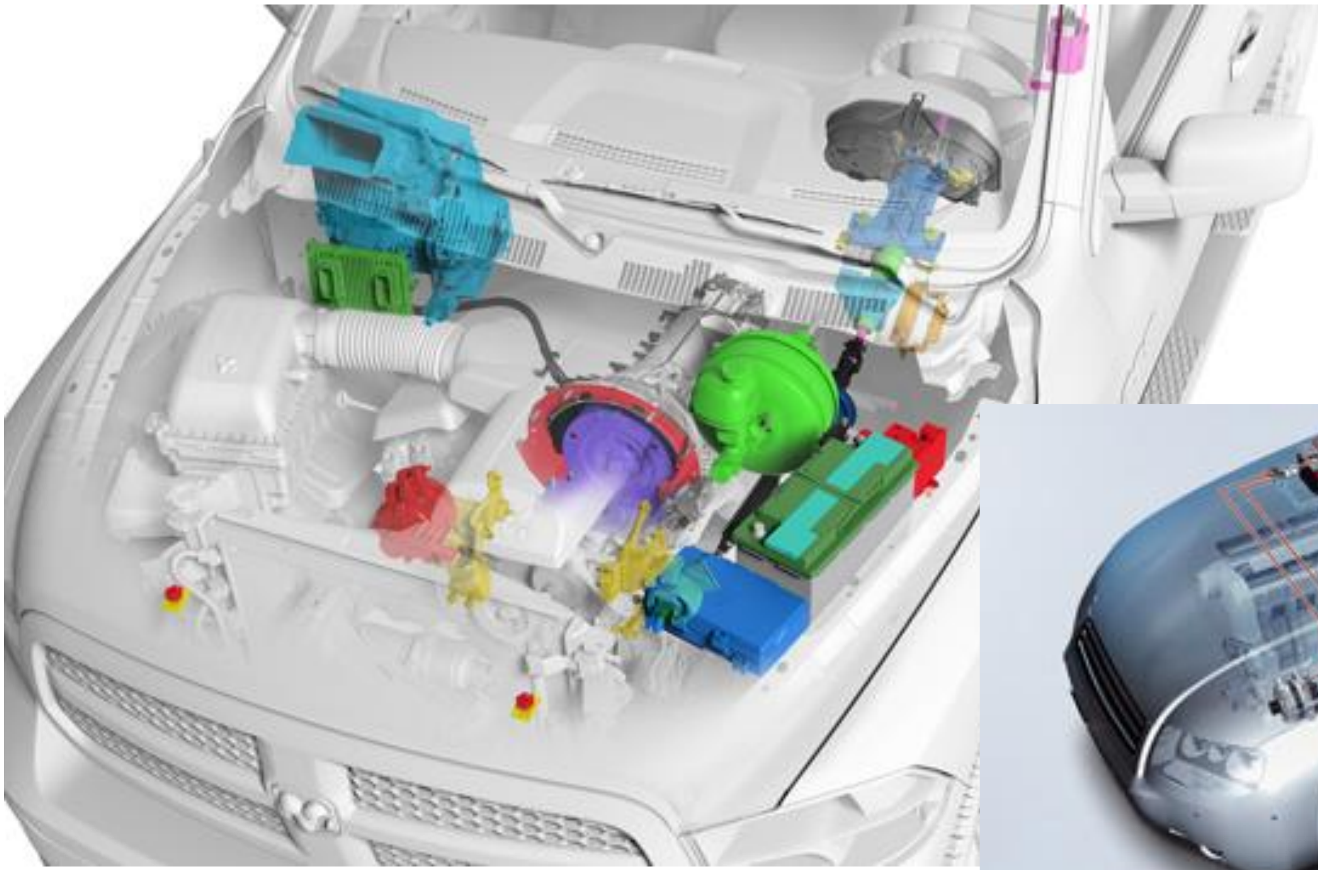
Barriers

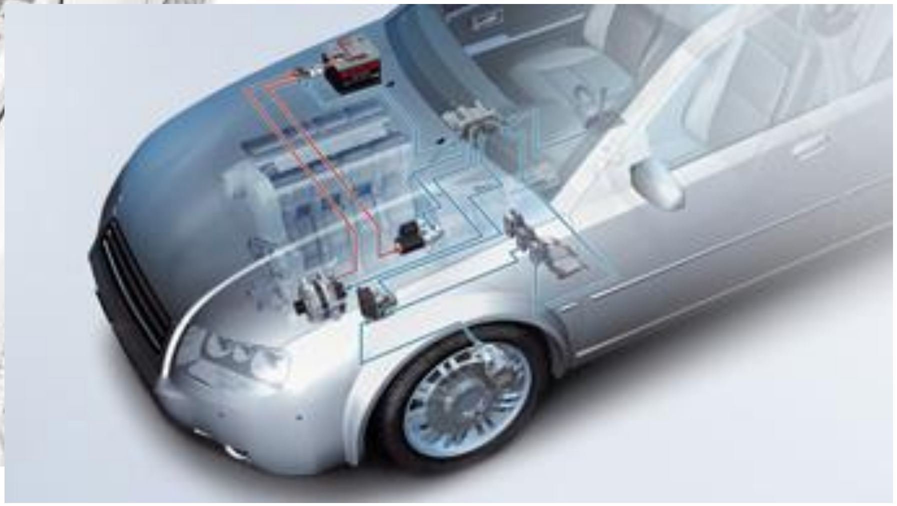
- Consumer adoption rates
  - COST!!
  - Range Anxiety (=COST)
- Manufacturing flexibility & infrastructure
  - Motors vs. IC-based Powertrains
- Development time for new vehicles (50-84 months)
- Penetration of 12V infrastructure in vehicle
- **Risk** vs. Reward
  - Large, additional development costs (over too few units)
  - Warranty

Automotive Energy Storage Solutions



Automotive Energy Storage Solutions – Start-Stop (Class 1)





Current State of the Automotive Industry – Start-Stop (Class 1)

End of Life Characteristics	Units	Target	
		Under hood	Not under hood
Discharge Pulse, 1s	kW	6	
Max discharge current, 0.5s	A	900	
Cold cranking power at -30 °C (three 4.5-s pulses, 10s rests between pulses at min SOC)	kW	6 kW for 0.5s followed by 4 kW for 4s	
Min voltage under cold crank	Vdc	8.0	
Available energy (750W accessory load power)	Wh	360	
Peak Recharge Rate, 10s	kW	2.2	
Sustained Recharge Rate	W	750	
Cycle life, every 10% life RPT with cold crank at min SOC	Engine starts/miles	450k/150k	
Calendar Life at 30°C, 45°C if under hood	Years	15 at 45°C	15 at 30°C
Minimum round trip energy efficiency	%	95	
Maximum allowable self-discharge rate	Wh/day	2	
Peak Operating Voltage, 10s	Vdc	15.0	
Sustained Operating Voltage – Max.	Vdc	14.6	
Minimum Operating Voltage under Autostart	Vdc	10.5	
Operating Temperature Range (available energy to allow 6 kW (1s) pulse)	°C	-30 to + 75	-30 to +52
30 °C – 52 °C	Wh	360 (to 75°C)	360
0 °C	Wh	180	
-10 °C	Wh	108	
-20 °C	Wh	54	
-30 °C	Wh	36	
Survival Temperature Range (24 hours)	°C	-46 to +100	-46 to +66
Maximum System Weight	kg	10	
Maximum System Volume	L	7	
Maximum System Selling Price (@250k units/year)	$	$220	$180

Huge challenge for today's PbA

Huge challenge for today's Lithium

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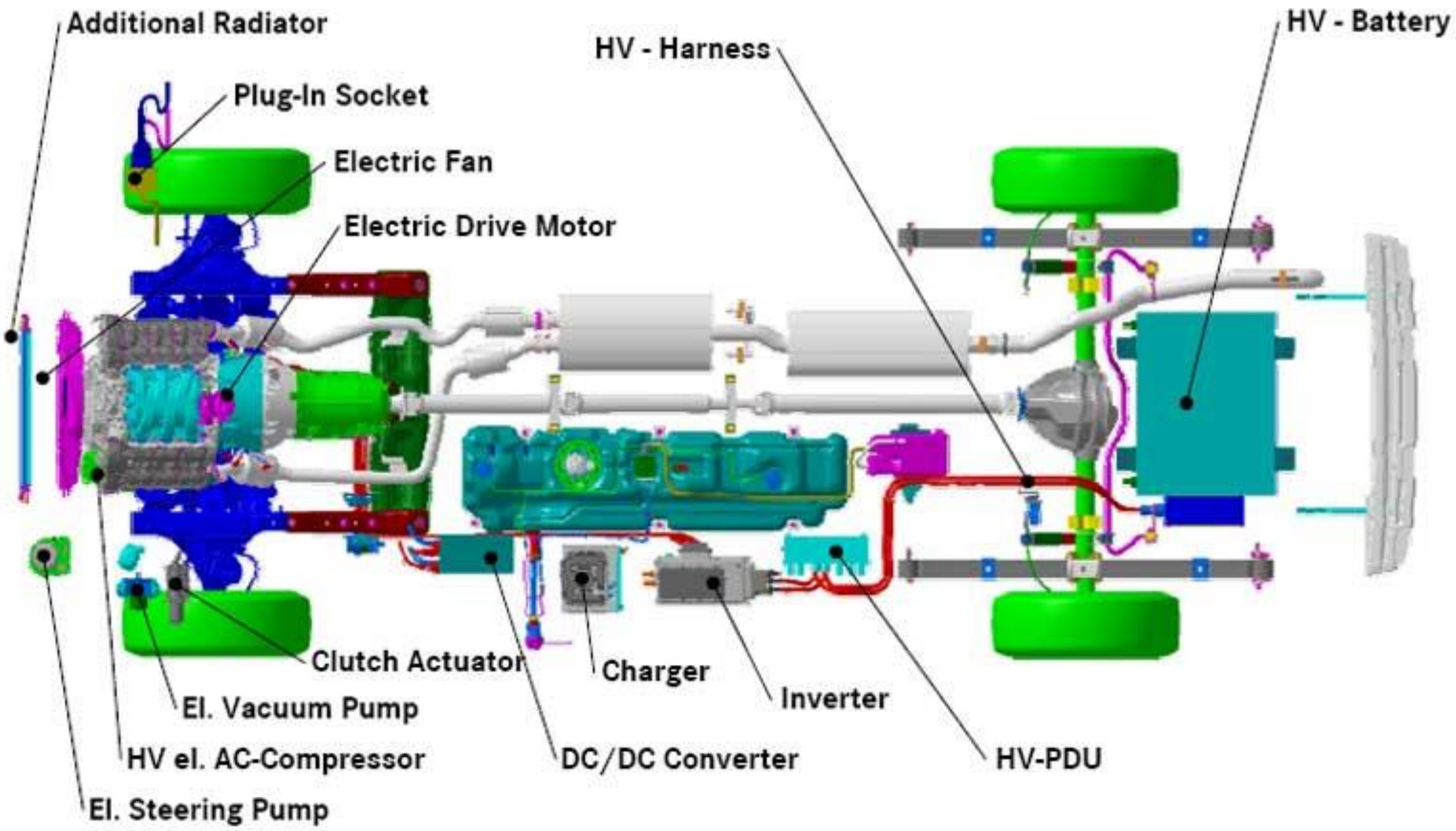
Automotive Energy Storage Solutions – Hybrid Vehicles (Class 2)



Current State of the Automotive Industry – Hybrid Vehicles (Class 2)

USABC Requirements of Energy Storage Systems for 48V HEV's at EOL

Characteristics	Units	Target
Peak Pulse Discharge Power (10 sec)	kW	9
Peak Pulse Discharge Power (1 sec)	kW	11
Peak Regen Pulse Power (5 sec)	kW	11
Available Energy for Cycling[1]	Wh	105
Minimum Round-trip Energy Efficiency	%	95
Cold cranking power at -30 °C (three 4.5-s pulses, 10s rests between pulses at min SOC)	kW	6 kW for 0.5s followed by 4 kW for 4s
Accessory Load (2.5 minute duration)[1]	kW	5
CS 48V HEV Cycle Life [2]	Cycles /MWh	75,000 / 21
Calendar Life, 30°C	year	15
Maximum System Weight	kg	≤8
Maximum System Volume	Liter	≤8
Maximum Operating Voltage	Vdc	52
Minimum Operating Voltage	Vdc	38
Minimum Voltage during Cold Crank	Vdc	26
Maximum Self-discharge	Wh/day	1
Unassisted Operating Temp Range (Power available to allow 5s charge and 1s discharge pulse) at min. and max. operating SOC and Voltage	°C	-30 to +52
30 °C - 52 °C	kW	11
0 °C	kW	5.5
-10 °C	kW	3.3
-20 °C	kW	1.7
-30 °C	kW	1.1
Survival Temperature Range	°C	-46 to +66
Max System Production Price @ 250k units/yr	$	$275

Power

[some chemistries are challenged]

Packaging

Cost

Current State of the Automotive Industry – Hybrid Vehicles (Class 2)

USABC Requirements at End of Life for **LEESS PA HEV**

End of Life Characteristics	Unit	PA (Lower Energy)	
2s / 10s Discharge Pulse Power	kW	55	20
2s / 10s Regen Pulse Power	kW	40	30
Discharge Requirement Energy	Wh	56	
Regen Requirement Energy	Wh	83	
Maximum current	A	300	
Energy over which both requirements are met	Wh	26	
Energy window for vehicle use	Wh	165	
Energy Efficiency	%	95	
Cycle-life	Cycles	300,000 (HEV)	
Cold-Cranking Power at -30°C (after 30 day stand at 30 °C)	kW	5	
Calendar Life	Years	15	
Maximum System Weight	kg	20	
Maximum System Volume	Liter	16	
Maximum Operating Voltage	Vdc	≤400	
Minimum Operating Voltage	Vdc	≥0.55 V_{max}	
Unassisted Operating Temperature Range	°C	-30 to +52	
30° -52°	%	100	
0°	%	50	
-10°	%	30	
-20°	%	15	
-30°	%	10	
Survival Temperature Range	°C	-46 to +66	
Selling Price/System @ 100k/yr)	$	400	

Charge Acceptance

Cycle Life

Cost

USABC Goals for HIGH POWER, LOWER ENERGY – ENERGY STORAGE SYSTEM (LEES) for POWER ASSIST HYBRID ELECTRIC VEHICLE (PAHEV) APPLICATIONS

NASA

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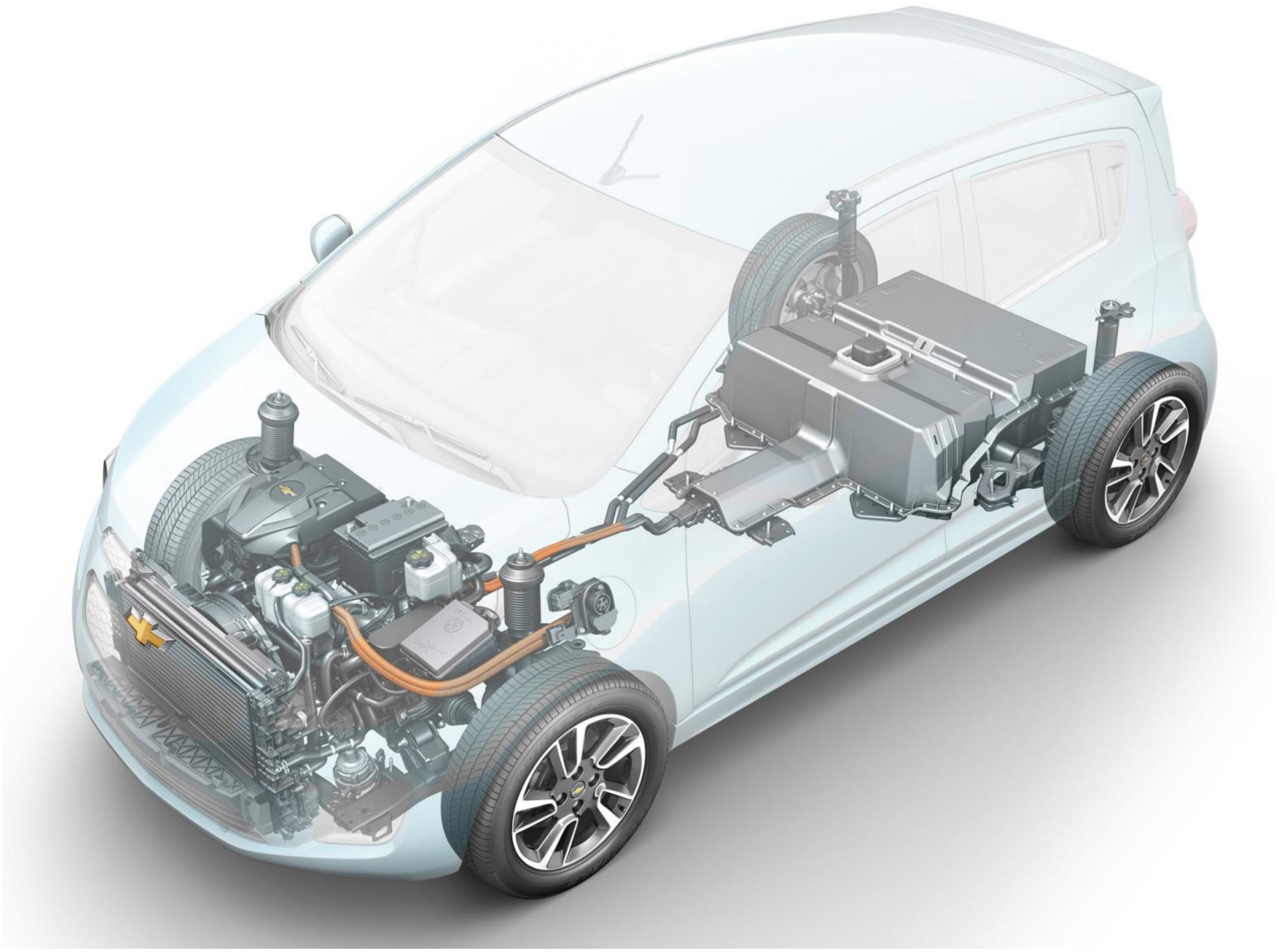
Automotive Energy Storage Solutions – Plug-in/Full Electric (Class 3)



Current State of the Automotive Industry – Plug-ins (Class 3)

USABC Requirements of Energy Storage Systems for PHEVs at EOL				
Characteristics	**Units**	**PHEV-20 Mile**	**PHEV-40 Mile**	**xEV-50 Mile**
Commercialization Timeframe		2018	2018	2020
AER	Miles	20	40	50
Peak Pulse Discharge Power (10 sec)	kW	37	38	100
Peak Pulse Discharge Power (2 sec)	kW	45	46	110
Peak Regen Pulse Power (10 sec)	kW	25	25	60
Available Energy for CD (Charge Depleting) Mode	kWh	5.8	11.6	14.5
Available Energy for CS (Charge Sustaining) Mode	kWh	0.3	0.3	0.3
Minimum Round-trip Energy Efficiency	%	90	90	90
Cold cranking power at -30°C, 2 sec - 3 Pulses	kW	7	7	7
CD Life / Discharge Throughput	Cycles/MWh	5000/29	5000/58	5000/72.5
CS HEV Cycle Life, 50 Wh Profile	Cycles	300,000	300,000	300,000
Calendar Life, 30°C	year	15	15	15
Maximum System Weight	kg	70	120	150
Maximum System Volume	Liter	47	80	100
Maximum Operating Voltage	Vdc	420	420	420
Minimum Operating Voltage	Vdc	220	220	220
Maximum Self-discharge	%/month	<1	<1	<1
System Recharge Rate at 30°C	kW	3.3 (240V/16A)	3.3 (240V/16A)	6.6 (240V/32A)
Unassisted Operating & Charging Temp Range	°C	-30 to +52	-30 to +52	-30 to +52
30°-52°	%	100	100	100
0°	%	50	50	50
-10°	%	30	30	30
-20°	%	15	15	15
-30°	%	10	10	10
Survival Temperature Range	°C	-46 to +66	-46 to +66	-46 to +66
Max System Production Price @ 100k units/yr	$	$2,200	$3,400	$4,250

Packaging =
Energy/Volume
Energy/Kg

Cost

Current State of the Automotive Industry – Full EVs (Class 3)

UNITED STATES ADVANCED BATTERY CONSORTIUM LLC

USABC Goals for Advanced Batteries for EVs - CY 2020 Commercialization

End of Life Characteristics at 30°C	Units	System Level	Cell Level
Peak Discharge Power Density, 30 s Pulse	W/L	1000	1500
Peak Specific Discharge Power , 30 s Pulse	W/kg	470	700
Peak Specific Regen Power , 10 s Pulse	W/kg	200	300
Useable Energy Density @ C/3 Discharge Rate	Wh/L	500	750
Useable Specific Energy @ C/3 Discharge Rate	Wh/kg	235	350
Useable Energy @ C/3 Discharge Rate	kWh	45	N/A
Calendar Life	Years	15	15
DST Cycle Life	Cycles	1000	1000
Selling Price @ 100K units	$/kWh	125	100
Operating Environment	°C	-30 to +52	-30 to +52
Normal Recharge Time	Hours	< 7 Hours, J1772	< 7 Hours, J1772
High Rate Charge	Minutes	80% ΔSOC in 15 min	80% ΔSOC in 15 min
Maximum Operating Voltage	V	420	N/A
Minimum Operating Voltage	V	220	N/A
Peak Current, 30 s	A	400	400
Unassisted Operating at Low Temperature	%	> 70% Useable Energy @ C/3 Discharge rate at -20 °C	> 70% Useable Energy @ C/3 Discharge rate at -20 °C
Survival Temperature Range, 24 Hr	°C	-40 to + 66	-40 to + 66
Maximum Self-discharge	%/month	< 1	< 1

Challenge for traditional large format cells

Fast Charge

-20 °C Operation

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Current Energy Storage Gaps - PbA

Priority areas for improving performance:

- **Higher cycle life**
- **Higher power density**
- **Better charge acceptance**
- **Lower battery weight**

Vocational Needs

- Start-stop with voltage stabilization system, potentially including lead-based AGM battery with supercapacitors
- Engine off while approaching a stop, but at vehicle speed <20 km/h (not only after complete vehicle standstill as today)
- "Stop-in-motion": Engine off at higher speeds whenever acceleration is not needed.

R&D Efforts - PbA

- **Battery manufacturers are currently working to implement the following general improvements:**
  - **Carbon nanotechnologies** – developing new types of additives to improve the conductivity of active materials
  - **High surface area doping materials** – increasing charge acceptance while avoiding hydrogen evolution (gassing)
  - **Low-cost catalysts** – recombining hydrogen and oxygen produced at regenerative brake events
  - **Light-weighting solutions** – developing new designs and materials

Current Energy Storage Gaps – Lithium ion

Priority areas for improved performance:

- **Reduced cost at battery pack level**
- **Increased energy and power density**
- **Improved battery lifetime**
- **Increased charge acceptance**
- **Better performance at cold (and hot)**

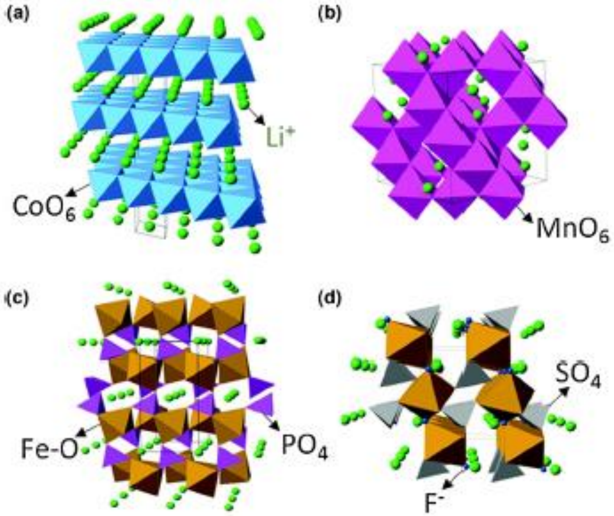
Vocational Needs

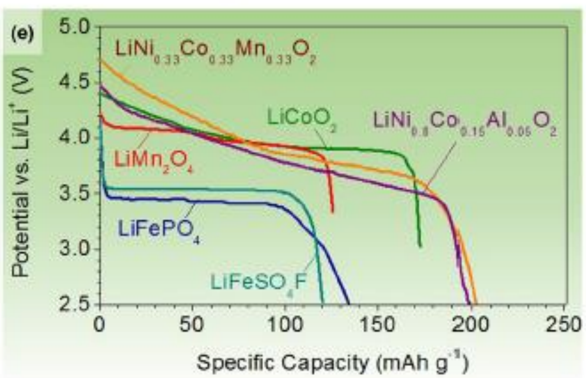
- Lithium-ion batteries will be used in advanced micro-hybrid and mild-hybrid vehicles.
- Lithium-ion batteries will be implemented in 48V dual battery systems together with a 12V lead-based battery
- Hybrid system (even 48V) support chassis systems, air conditioning compressors, and regenerative braking and more.

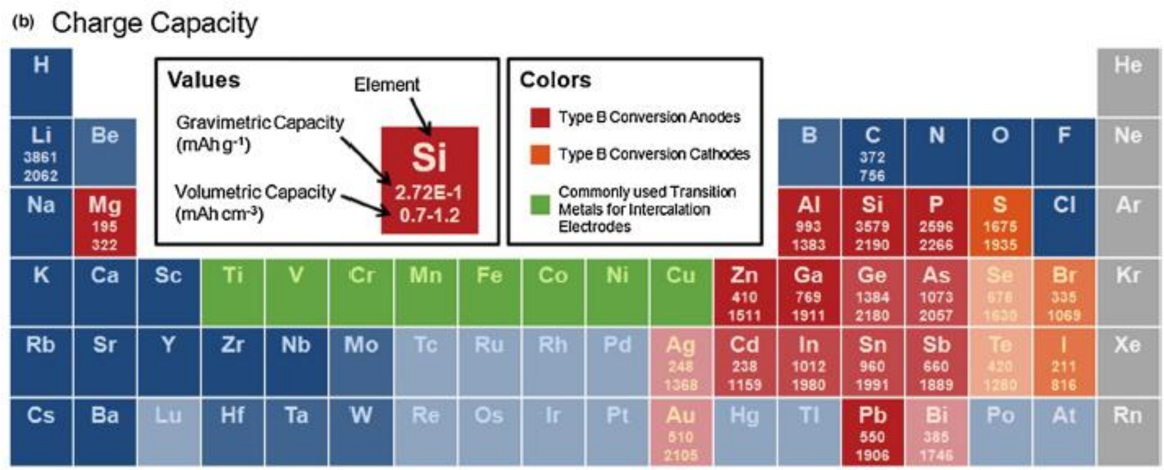
Current Engineering Efforts – Lithium ion

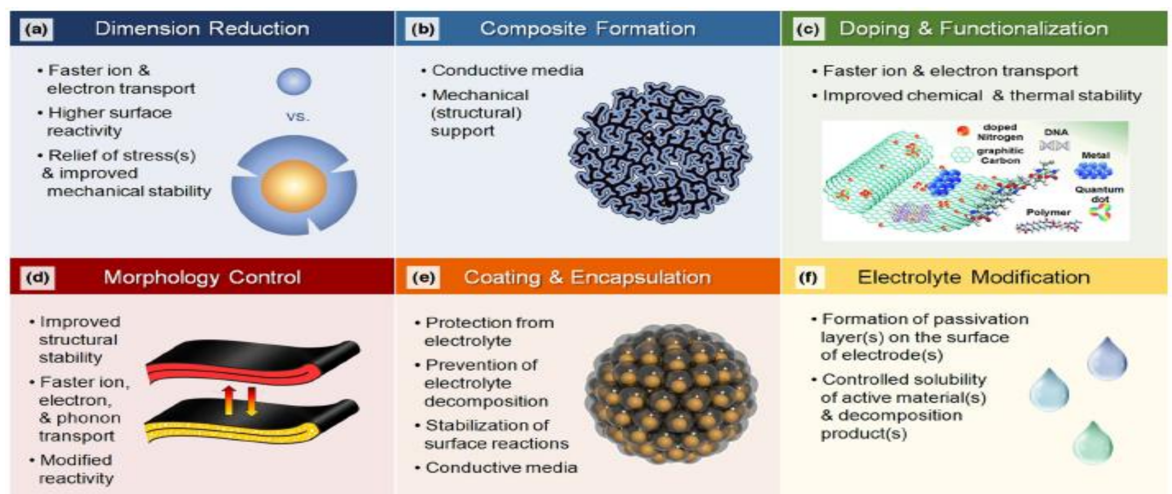
- **Performance and Cost - a materials play**
  - Improvement of cell materials and components
    - Anode, Cathode, Separator, Electrolyte
  - Lower cost cell mechanical design
  - Improvement of materials properties
  - Scaling up in production of large cell formats

Current R&D Efforts – Lithium ion









Mid-Term R&D Efforts – Lithium ion

- **Silicon Anode Batteries**
  - Challenges: Volumetric fluctuations, cracking, poor cycle life
- **Lithium Sulphur**
  - Challenges: High mechanical stress, unwanted reaction with electrolytes, nonlinear discharge and charge response
- **Solid State (thin film) Batteries**
  - Challenges: Difficulty getting high current across solid-state interfaces
- **Lithium Capacitors**
  - Challenges: Self-discharge, energy density, thermal design
- **Lithium Air Batteries**
  - Challenges: Limited by the oxygen evolution and oxygen reduction kinetics, especially oxygen evolution
- **Magnesium (anode) Batteries**
  - Challenges: Chemistry involved in making a magnesium-ion battery work efficiently has yet to be perfected (some promising work)

Current Engineering Efforts – Lithium ion

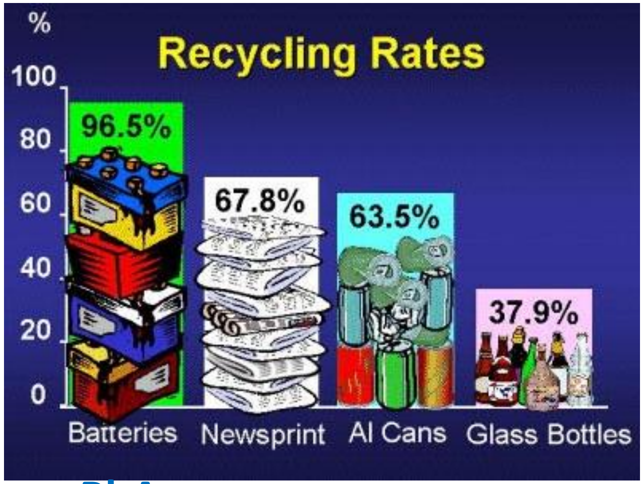
- **Systems integration (pack)**
  - Progress is being made in optimization and standardization of mechanical designs
  - Better understanding of Battery Management System (BMS) functions, components and interfaces
  - More advanced Thermal Management systems
    - Improve range of operating conditions
    - Reduce system complexity

Current Engineering Efforts – Lithium ion

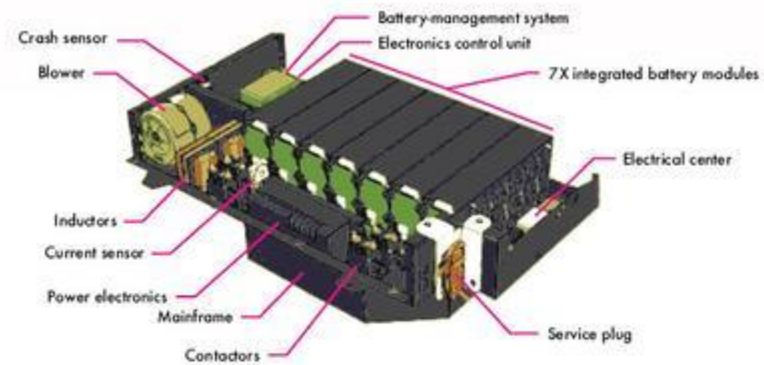
- **Safety**
  - Efficient and **high fidelity state-of-function monitoring** techniques
  - Advanced **state-of-charge/ state-of-health** indicators
  - Cell diagnostic and supervision systems to support the **lifecycle management of ageing**
  - Realistic standards for **abuse tolerance** are being released
  - Need the concomitant improvements to the **robustness of cell and pack design**

Current Engineering Efforts – Lithium ion

- **Recyclability**
  - With the recycling industry for lithium ion batteries still in its infancy, a variety of actors are also looking at how to optimize the **separation of lithium-ion battery components** at the battery's end-of-life.



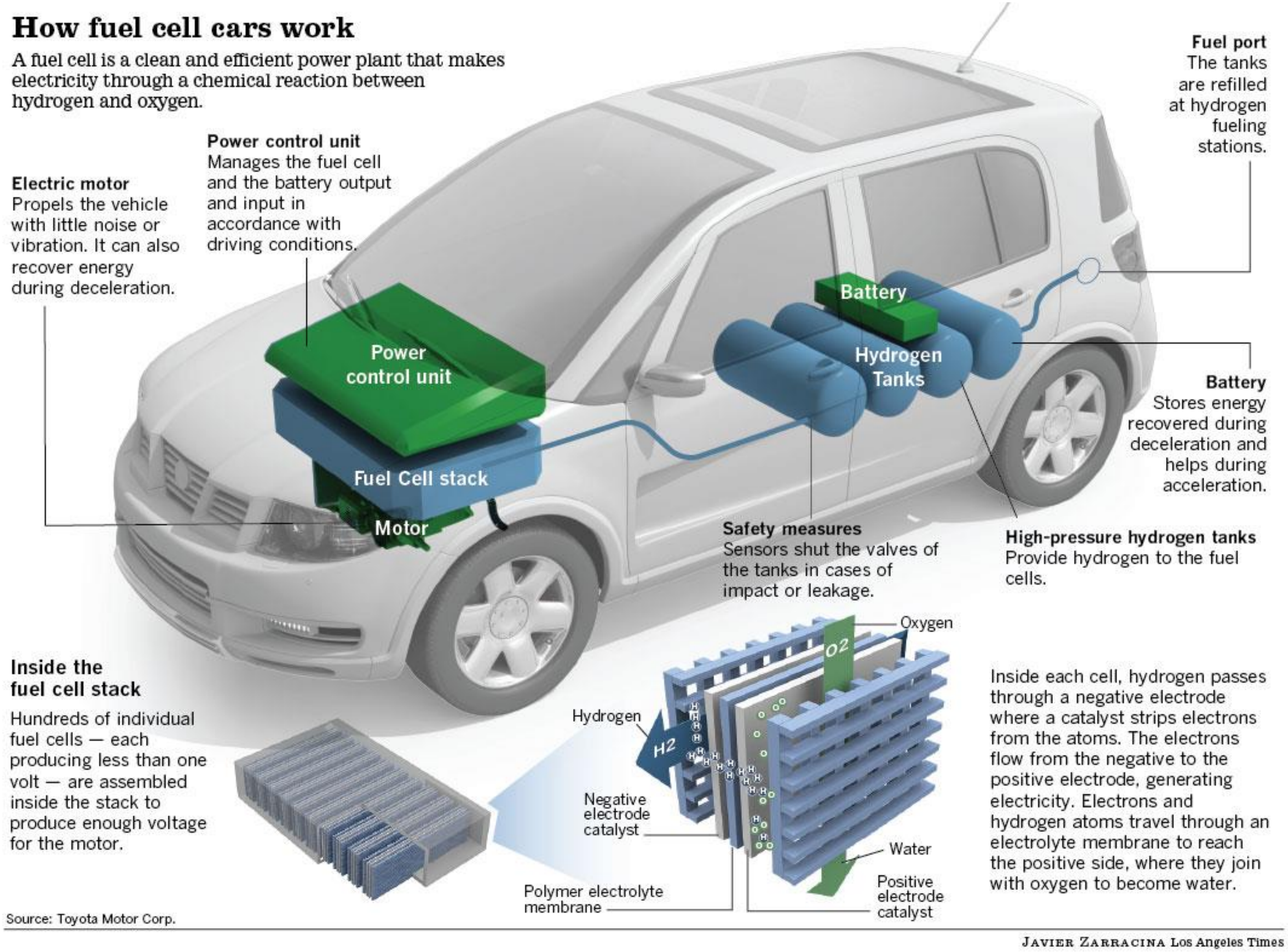
PbA



1. The Nanophosphate chemistry power-management module from A123Systems includes seven lithium-iron-phosphate batteries and the necessary control electronics for a plug-in hybrid electric vehicle.

Lithium

Current R&D Efforts – Automotive Fuel Cell



Current R&D Efforts – Automotive Fuel Cell

Advantages

- Water is the only discharge (pure H_2)
- Potential transition 2020+
- Japanese investment in market adoption
- Plays well in California

Disadvantages

- CO_2 discharged with methanol reform
- Little more efficient than alternatives
- Technology currently expensive
- Hydrogen often created using “dirty” energy (e.g. coal)
- Pure hydrogen is difficult to handle
  - Refilling stations, storage tanks
- Perception of “future technology”
- Limited number of suppliers

Opportunities for Ohio – Already #2 or #3 in Auto Supply Chain

Area	Ohio Opportunity
1. **Cell Chemistry (ies)**	1. Materials, Binders, Additives
2. **Cell Experience**	2. NASA/Defense/Drones early users of emerging cell chemistries
3. **Control Systems/Electronics**	3. Strong Supply Base (auto, commercial, industrial)
4. **Recycling**	4. Design/Manufacturing for Recyclability; automotive recycling value chain
5. **PbA**	5. Continue leadership in PbA
6. **Lithium Pack Manufacturing/Integration**	6. Fill gap between OEMs and nameplate customers
7. **Reduce Time/Cost of product validation testing**	7. In a world with increasing demands for more safety, durability and product validation

Future Opportunities for Ohio

Area	Ohio Opportunity
1. **Lightweight Materials**	1. Migration of aluminum, lightweight steel, and performance plastics into vehicles and packs
2. **Form Factors (Design + Materials)**	2. Reduce volume, add other functional roles
3. **Intelligent vehicles**	3. Lower-cost, lower energy sensors and systems to maintain load levels
4. **Fuel Cells**	4. Because we are at NASA and someone here is thinking about it!
5. **Reduce use of rare earth metals**	5. Issue across all the industries
6. **BMS/Control Systems**	6. Security in a remote, V2I, V2V world

Q&A